POLAR LAYERED TERRAINS: LINKS BETWEEN THE MARTIAN VOLATILE AND DUST CYCLES. R. W. Zurek, Jet Propulsion Laboratory, California Institute of Technology (MS 183-335, 4800 Oak Grove Drive, Pasadena, CA 91109; rzurek@jpl.nasa.gov)

Introduction: The nature, origin and evolution of the polar layered terrains are a major mystery of Martian climate. Almost every aspect of these enigmatic terrains surrounding, and probably underlying, the polar residual ice caps is in contention. Are the polar laminae forming today? Are they inactive or even eroding, being mere relics of the past? Are the north and south polar layered terrains fundamentally different in composition, age or process? Are they a physical record of past, possibly cyclic, climate change and, if so, can we learn to read that record?

We know from past Mariner 9 and Viking orbital observations that there are layered terrains at high latitudes, defined by alternating bands of visually lighter and darker material appearing in stacks hundreds of meters thick with individual bands as thin as could then be resolved (tens of meters). These bands are exposed at the edges of the layered terrains and of the chasmae, troughs and the few craters that cut into them, although there are also areas where the layering appears in apparently gently sloping ground. The layers are often continuous for hundreds of kilometers, but significant unconformities are also observed. (See Thomas et al [1] for a review.)

In this talk, aspects of the polar layered terrains will be reviewed with emphasis on issues likely to be addressed with data from ongoing and near-term flight missions to Mars. Particular attention will be given to what might be learned from observing the present seasonal cycles of dust, water and carbon dioxide on Mars, in conjunction with in situ data from one site on the south polar layered terrain.

Polar Layered Terrain and Climate Change: The mere presence of layering in the polar regions suggests a cyclic climate change. The presence today of order ten precipitable microns of column atmospheric water and, during dust storms, of a few microns of dust in an atmospheric column, suggest that an annual layer forming now might be a few tens of microns thick (allowing for some concentration of these fields in the polar regions) [2]. That sets a time scale for formation of a meter of layered material of the order of several hundred thousand years. Since radiation in the polar regions is affected on similar time scales by changes in the obliquity of the rotation pole, eccentricity of the orbit and seasonal phasing of perihelion and aphelion, astronomical forcing has been proposed as the agent of change, just as it is believed to be part of the climate forcing for Earth's ice ages [3]. If layered terrains are indeed built year by year in an annual process modulated on much longer time scales, then the modeling of their formation depends critically upon understanding the interplay on Mars of the three key seasonal cycles of dust, water and carbon dioxide [4,5,6] and how that interplay varies on climatic time scales.

Other clues to the nature of the south and north polar layered terrains may lie in their very different residual ice caps (i.e., those ice fields that currently survive through summer). The north permanent ice cap is known to be water ice and covers most of the northern layered terrain. The north residual ice cap is significantly larger than its southern counterpart, which is composed of carbon dioxide ice, despite the fact that the perihelion of the highly eccentric orbit of Mars occurs in late southern spring and so that the south polar residual ice fields are being blasted by the highest rates of annual insolation. The survival of the southern permanent cap depends upon its observed higher albedo [7]. The cause of this reflective difference is not known, but there are observations that suggest the higher insolation itself may play a role [8], perhaps with darker material on the ice cap warming and burrowing into the frosts.

Present Role of the Seasonal Cycles: It has been argued that planetary-scale dust storms are an important player in forming a layered terrain (today), as these storms produce the most opaque dust hazes with column abundances several microns thick and may perturb the atmospheric circulation in such a way that dust and water are more easily moved into the polar regions. Once in the winter polar region, condensation of water and carbon dioxide onto the dust suspended in the atmosphere accelerates the fall of the dust (and water) to the surface, augmenting direct accumulations onto the seasonally condensing carbon dioxide cap [2].

Dust. If a planet-wide dust storm is required to build a layered terrain, then the existence of a low-latitude trigger for initiating these storms is required, and not just insolation changes in the polar regions. Furthermore, some factor less than one needs to be included in the layer thickness calculation, since today planetary-scale dust storms do not occur each Martian year [9]. Given that the largest dust storms presently occur during southern spring and summer, when Mars is closest to the Sun, a critical role for planetary-scale dust storms would suggest that layers are being formed in the north polar region during northern fall and winter and not in the south during the present epoch. However, recent observations by the MGS Thermal Emission Spectrometer (TES) [10] indicates that even moderate-sized (i.e., regional) dust storms can have far-flung consequences, and these storms are considerably more frequent than are nearly hemispheric or global storms and can occur in all seasons [9]. There remains a tendency for all great dust storms to occur more often during southern spring and summer, but there is an observational bias to this historical, Earth-based data set which is being tested with new, ongoing Earth-based and HST observations of Mars.

Water. What about the other supposed key ingredient of a polar lamina, namely water? The conventional view was that water vapor was only a passive player in the formation of a layered terrain, except in the polar region itself where it, along with condensing carbon dioxide, would scavenge dust from the atmosphere and be incorporated into the surface of a seasonally condensing carbon dioxide cap. This conventional view of the water cycle has been challenged by R. T. Clancy [11], who noted that water ice cloud formation could be the major player in the global circulation and in the transport of dust and water if water ice, through its scavenging and removal of dust particles suspended in the atmosphere, were the primary hemispheric control in the vertical distribution and lateral redistribution of atmospheric dust. The present eccentricity of the orbit of Mars and the occurrence of aphelion during late northern spring radiatively leads to colder temperatures during northern spring and summer, resulting in more frequent and widespread water ice clouds. This seasonally lower condensation level, it is argued, then limits water to the northern hemisphere or preferentially traps it there when water is brought from the southern hemisphere. This confinement is not counterbalanced during the opposite seasons since the atmosphere is warmer then and water may be more easily transported.

There are some complex issues here regarding the height of the condensation level and the altitude of the effective transport level which need to be quantified. In any case the hypothesis assumes that water ice particles will have short fall times compared to transport times, so that condensation implies less poleward transport; this remains to be demonstrated in ways that can be confidently extrapolated back into the past (or future). Accepting these arguments, layered terrains again would form in the polar region which has the perihelic winter (with water lost from the perihelic summer hemisphere) whenever the orbit is significantly elliptical.

Carbon Dioxide. That leaves consideration of the third cycle, namely that of carbon dioxide. In the two scenarios discussed above, the role of carbon dioxide is to sequester the dust and water injected elsewhere into the atmosphere into the winter polar cap. However, given that there is at present a (possibly) permanent carbon dioxide cap at the south pole, it has been argued that atmospheric water vapor will tend to be lost, over time, to this coldest spot on the planet [13]. Dust can also move into the south polar area, either as local dust storms follow the seasonal cap retreat in the south or as regional and larger storms come and go. In this scenario layered terrain is being formed in the south polar residual cap (and possibly on the adjacent layered terrain) and one is left to understand the climatic factors that control the presence of the carbon dioxide residual ice cap itself.

Formation. Once water ice and dust get mixed into the seasonal (or permanent) carbon dioxide cap, how does it form a layer? We understand very little of the microphysics involved, even to the extent of understanding the exchange of water between the atmosphere and the subsurface and the aging of ice-dust mixtures in the Martian polar environment.

Erosion. What are the processes that erode the layered terrain? Certainly, strong winds occur over these polar regions. Pressure gradients due to condensation or sublimation of carbon dioxide and to temperature gradients with latitude can drive strong winds, particularly off the layered terrains and polar residual caps which are elevated above the surrounding terrains. The presence of sand in the northern dune ergs and in numerous (but smaller) locales in the south can increase the effectiveness of aeolian abrasion. Recent MGS Mars Orbiter Camera (MOC) images indicate that at least the northern dune fields are active, and the southern ones may be as well. However, the presence of craters in the south polar layered terrains indicates that recent erosion rates are small in the south and may have been that way for several tens of millions of years [12]. Absence of similar numbers of craters in the north may indicate a more active surface or a younger surface, though possibly only that of the residual north polar water ice cap which covers much of the northern layered terrain.

Ages. In both the north and south polar regions, the layered terrains stand on top of older terrain. In the south, layers were deposited on top of the heavily cratered terrain that covers much of the southern hemisphere. In the north the plains surrounding the polar layered units are younger than the southern ancient terrain, but still old compared to the layered terrains themselves. It has been suggested that at least the south polar layered terrain may be a relic from the past and is not actively forming during the present climate epoch. However, the same cratering rate analysis [12] indicates that even the south polar layered terrain cannot date back in its entirety to the ancient climate (a billion years or more ago). One of many complications in establishing the age of the polar deposits is the likelihood that the layered terrains are not uniformly deposited in the polar regions; that is, different parts of the surface may have been formed during different climate epochs; neither the top nor the bottom may be the same age everywhere in the layered terrain.

There are also some observational data, albeit rather indirect, that suggest the south polar residual ice cap is not permanent. A residual cap of carbon dioxide ice and frost is very cold, since vaporization of the frost maintains temperature at the frost point (which decreases with pressure and therefore altitude). Thus, the south residual cap will act as a cold trap for water vapor [13]. Observations in 1969 of column water abundances higher than the Viking amounts observed in 1976-77 suggest a different interhemisphere exchange of water than during the Viking period or a southern hemisphere surface source, perhaps exposed by a vanishing carbon dioxide ice cap [14]. However, the exposure of bare ground or even a water ice block beneath the present residual ice cap would permit heat to be stored during summer at depth where it would warm the surface later in fall and winter, slowing the formation of a seasonal carbon dioxide frost deposit deep enough to survive the next summer. Once lost, then, the reformation of a residual carbon dioxide cap becomes problematic.

Mars Surveyor Program: One reason that progress in understanding the polar regions has been slow is that we have lacked even the most basic geophysical data (e.g., altimetry). That is now changing dramatically.

Mars Global Surveyor (MGS). Data from MGS acquired during last summer's Science Phasing Orbit and more recently from its nominal mapping mission are already providing detailed information about the polar regions. For instance, one difference between the two polar layered terrains and their residual ice caps that was long suspected [8] and which is now confirmed is that the south polar region is several kilometers higher than is the north polar cap. The acquisition of high-resolution MOC images and of precise Mars Orbiter Laser Altimeter (MOLA) altimetry is already impacting our understanding of the polar regions and of layered terrain. For instance, MOC has shown that extensive layering is not confined to the polar regions, but occurs elsewhere on the planet, as in Vallis Marineris, but it has also shown that fine-scale layering and fine-scale topography (observed at ~ 2 m spatial resolution) do exist in the polar layered terrains. Meanwhile, MOLA observations indicate that one must understand the three-dimensional aspects of the polar terrains; for example, the north polar outliers, dune fields and residual ice cap may not be as disjoint as surface images alone indicate. All of these data and much more will be discussed in other conference sessions.

Mars Polar Lander/Mars Climate Orbiter. On December 3 of this year the Mars Polar Lander (MPL), with its LIDAR and its integrated Mars Volatiles and Climate Surveyor (MVACS) payload, will land on one of the more equatorward lobes of the south polar layered terrain. During its descent to the surface the MPL Mars Descent Imager (MARDI) will acquire a set of images that can connect Orbiter images acquired by Mariner 9, Viking, MGS and the Mars Climate Orbiter (MCO, launched in December of last year) with multi-spectral panoramas of the MPL landscape and its mineralogy acquired by the MVACS Surface Stereo Imager (SSI). The SSI images in turn will provide context for close-up observations of surface and subsurface texture by the MVACS Robotic Arm Camera. Meanwhile the MVACS Surface Thermal Probe will provide ground-truth measurements of near-surface thermal properties that can be compared with surface thermal properties derived from Viking IRTM, MGS TES, and MCO PMIRR (Pressure Modulator IR Radiometer) observations.

MVACS and the LIDAR (provided by the Russian Space Research Institute) will also characterize the local meteorology over the compressed seasonal cycle that occurs at high latitudes during spring and summer, following the MPL landing in late spring. This will include the first-ever measurement of the near-surface atmospheric concentration of water vapor. Meanwhile, the MVACS Robotic Arm will trench approximately a half meter into the surface in a search for ground ice and subsurface layering; it will also deliver soil samples to the Thermal Evolved Gas Analyzer (TEGA) which will search for water and carbon dioxide as ice, as adsorbed materials and finally as chemically bound components of soil minerals. A hundred kilometers further north (equatorward) of the MPL site, the two DS-2 microprobe penetrators will also hunt for subsurface ice during their brief period of landed operations.

From orbit, MGS MOC and MCO Mars Color Imager (MARCI) data will provide unprecedented coverage of the polar regions at a variety of spatial resolutions and spectral sensitivities. The MGS TES and MCO PMIRR will monitor the growth and retreat of the seasonal polar caps and better quantify the albedo of the residual ice caps. PMIRR and TES will profile atmospheric temperatures, dust and condensates while PMIRR will also vertically profile atmospheric water vapor (as may TES). These investigations will provide the data needed to understand more quantitatively the transport of water and dust on Mars, including transport into the polar regions.

Mars Surveyor '01. In October 2001, the Mars Surveyor '01 (MS'01) Orbiter will begin aerobraking at Mars. Once in its mapping orbit, the MS'01 Gamma Ray Spectrometer instrument suite will map the presence of near-surface water (hydrogen), while the THEMIS instrument with its thermal infrared and visual images will provide improved moderate resolution, spectral mapping of the planet.

Summary: While these data will tell us much more about the polar layered terrains, there are clear limitations to having data from one Mars year at one site on the polar layered terrain. No future landers are planned to explore the polar terrains further, including landing in the north, nor to explore in situ the permanent polar ice caps. Perhaps the most severe limitation will be the absence of age dating of the layered terrains and the examination of material from several meters depth.

Nevertheless, the expanded global reconnaissance of Mars over three Mars years and the knowledge at one polar site of whether ice exists close to the surface, of whether very fine scale layering is present, of the behavior of near-surface water, and of a general characterization of the landscape and near-surface atmosphere will undoubtedly improve our understanding of the enigmatic polar layered terrains, even as the data surprise us with new mysteries.

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Acknowledgment: Work by the author was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.